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FORM PTO-139C (REV. 11-2000) U S DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY 'S DOCKET NUMBER 136.157

U.S. APPLICATION NO (If known, see 37 CFR 1 5 09/786173

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/FR99/02076	01 September 1999	04 September 1998

TITLE OF INVENTION METHOD FOR ESTIMATING MOVEMENT BETWEEN TWO IMAGES

APPLICANT(S) FOR DO/EO/US Nathalie Laurent-Chatenet, Patrick Lechat and Henri Sanson

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☐ This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (21) indicated below.
4. ☐ The US has been elected by the expiration of 19 months from the priority date (Article 31).
5. ☒ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. ☐ is attached hereto (required only if not communicated by the International Bureau).
   b. ☒ has been communicated by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☒ An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
   a. ☒ is attached hereto.
   b. ☐ has been previously submitted under 35 U.S.C. 154(d)(4).
7. ☒ Amendments to the claims of the International Aplication under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. ☐ are attached hereto (required only if not communicated by the International Bureau).
   b. ☐ have been communicated by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☒ have not been made and will not be made.
8. ☐ An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371 (c)(3)).
9. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)). (unexecuted)
10. ☐ An English lanugage translation of the annexes of the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11 to 20 below concern document(s) or information included:

11. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☒ A FIRST preliminary amendment.
14. ☐ A SECOND or SUBSEQUENT preliminary amendment.
15. ☐ A substitute specification.
16. ☐ A change of power of attorney and/or address letter.
17. ☐ A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.
18. ☐ A second copy of the published international application under 35 U.S.C. 154(d)(4).
19. ☐ A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).
20. ☒ Other items or information: French-language International Preliminary Examination Report

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U.S. APPLICATION NO (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO	ATTORNEY'S DOCKET NUMBER
09/786173	PCT/FR99/02076	136.157

21. [x] The following fees are submitted:

	CALCULATIONS	PTO USE ONLY
BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)):		
Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1000.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO **$860.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$710.00**		
International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$690.00**		
International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 860.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than [ ] 20 [ ] 30 months from the earliest claimed priority date (37 CFR 1.492(e)).	$ --	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE	$	
Total claims	24 - 20 =		x **$18.00**	$ 72.00	
Independent claims	1 - 3 =	0	x **$80.00**	$ --	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$270.00**	$ --	

TOTAL OF ABOVE CALCULATIONS =	$ 932.00	
[ ] Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2. +	$ --	
SUBTOTAL =	$ 932.00	
Processing fee of **$130.00** for furnishing the English translation later than [ ] 20 [ ] 30 months from the earliest claimed priority date (37 CFR 1.492(f)).	$ --	
TOTAL NATIONAL FEE =	$ 932.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +	$ --	
TOTAL FEES ENCLOSED =	$ 932.00	
	Amount to be refunded:	$
	charged:	$

a. [x] A check in the amount of $ 932.00 to cover the above fees is enclosed.

b. [ ] Please charge my Deposit Account No. ______ in the amount of $ ______ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. [x] The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 14-1080 . A duplicate copy of this sheet is enclosed.

d. [ ] Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. **Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137 (a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO.

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40,926
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09/786173

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

National Phase of PCT/FR99/02076

International Filing Date: September 1, 1999

Inventors: Nathalie Laurent-Chatenet, Patrick Lechat and Henri Sanson

Title: *Method for Estimating Movement Between Two Images*

Priority: French Application No. 98 11227; Filed September 4, 1998

Attorney Docket: 136.157 Customer No. 023907

PRELIMINARY AMENDMENT

DO/EO/US
Assistant Commissioner for Patents
Washington DC 20231

Sir:

This Preliminary Amendment is directed to a new U.S. application as identified above.

Please enter this preliminary amendment prior to calculating the fees.

Please amend the application as follows:

IN THE SPECIFICATION

Page 1, after the title insert the heading -- BACKGROUND OF THE INVENTION --;

Page 3, line 14, insert the heading -- OBJECTS AND SUMMARY OF THE INVENTION --;

Page 4, line 31, insert the heading -- BRIEF DESCRIPTION OF THE DRAWINGS --;

Page 5, line 8, insert the heading -- DESCRIPTION OF THE PREFERRED EMBODIMENTS --.

IN THE CLAIMS

Claims 4 and 5, line 1, cancel "one of claims 1 to 3" and substitute -- claim 1 --;

Claim 6, line 1, cancel "one of claims 1 to 5" and substitute -- claim 1 --;

Claims 9, 10 and 11, line 1, cancel "one of the preceding claims" and substitute -- claim 1 --;

Claims 12 and 13, line 1, cancel "one of claims 1 to 11" and substitute -- claim 1 --;

Claim 14, line 1, cancel "one of the preceding claims" and substitute -- claim 1 --;

Claim 16, line 1, cancel "or 15";

Claim 18, line 1, cancel "one of claims 12, 13 or 17" and substitute -- claim 1 --;

Claim 19, line 2, cancel "one of claims 1 to 18" and substitute -- claim 1 --;

Claim 21, line 2, cancel "one of claims 1 to 18" and substitute -- claim 1 --;

Claim 23, line 1, cancel "one of the preceding claims" and substitute -- claim 1 --.

IN THE ABSTRACT

Please add page 21 containing an Abstract of the Disclosure.

REMARKS

This application has been amended to insert headings in the specification, to eliminate the multiple dependencies in the claims, and to add an Abstract of the Disclosure. Entry of the amendments and early consideration and allowance are respectfully requested.

The Commissioner is hereby authorized to charge payment of any additional fees which may be required at any time during the prosecution of this application, or credit any overpayment, to Deposit Account No. 14-1080.

Respectfully submitted,

Lisa A. Brzycki

Dated: February 28, 2001

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ABSTRACT OF THE DISCLOSURE

A method for estimating motion between two digital images I_1 and I_2, with brightness Y_1 and Y_2 for generating, for each point of coordinates x, y of image I_2 a motion vector $\vec{d}(x,y)=(d_x,d_y)$ so as to form an image $\hat{I}_2$ from image I_1 with brightness $\hat{Y}_2(x,y)=Y_1(x-d_x,y-d_y)$ which is an approximation of image I_2. The method consists in using a model of finite elements and a differential method for determining the motion field of image I2. The mesh associated with the model of finite elements is refined as the motion estimation is being carried out.

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METHOD FOR ESTIMATING MOVEMENT BETWEEN TWO IMAGES

The present invention concerns a method for estimating movement between two numerical images.

The movement between two successive images, I_1 and I_2, is generally defined in the form of a movement field associated with either of the images , I_1 and I_2 and constituted by movement vectors, each relating to one point of the image concerned. The movement vector is a two-dimensional vector representative of the difference of position between the pixel of the image I_1 and the associated pixel of the image I_2 relating to the same physical point of the filmed scene.

An evaluation of movement is useful in fields for processing the image requiring a knowledge of movements or disparities between two images. By way of examples, it is possible to cite the following spheres of applications :

- the compression of images : the evaluation method is used to limit the amount of data to code an image, the images being defined in relation to one another ;
- the compression of data in spaces of dimension greater than 2 ;
- video coding : the movement field defined from already coded images is then used to predict the next image ;
- medical imagery: the method for estimating the movement between two images is used to conduct an analysis of the movement of the heart for example ;
- remote monitoring : the method can be used to monitor road traffic ;
- three-dimensional reconstruction from multi-view images: the method is used to estimate disparities between various views.

So as to obtain this movement field, a method is known on how to break down the image into finished elements. These finished elements, which may for example be triangles or quadrangles, are determined by a meshwork whose nodes correspond to the tops of the finished elements. A movement vector is calculated for each node of the meshwork. Then, via the bias of an interpolation function, it is possible to deduce from this a movement vector for each point of the image in

question. The movement field is thus determined by a model of finished elements defining the meshwork used to partition the image into finished elements and the interpolation function making it possible to calculate the movement vector at any point of the image.

The meshwork used can be regular or irregular and needs to selected as sufficiently dense so as to model as best as possible the movement between the two images without however requiring an excessive quantity of calculation or data to be transmitted. This choice is made once only at the start of the method and this meshwork generally remains the same throughout the estimate.

The calculation of the movement vectors of the nodes of the meshwork can be carried out according to various methods. First of all there are putting into correspondence or "matching' methods consisting of testing a discrete set of possible values of movement vectors for each node of the meshwork and of retaining the best vectors according to a given criterion. A second method known as a transformed method consists of using the properties of the Fourier transform and its extensions so as to convert the movement into a phase jump in the transformed space. Finally, there is a third method known as a differential method for determining the movement vectors by optimising a mathematical criterion (for example a quadratic error between the image and its aforesaid value with the movement field). This method is most frequently used for estimating movement with modelisation by finished elements. A conventional differential method for optimising movement vectors is the Gauss-Newton method. The present application concerns more particularly the movement estimation method family using a model of finished elements and a differential method to determine the movement field.

Although widely used, this type of method does however have several drawbacks. The meshwork selected at the start of the method may prove to be inappropriate with respect to the semantic contents of the image, certain zones of the image requiring a denser meshing and others a more aerated meshing. In addition,

under the effect of the field of the movement vectors of the nodes of the meshwork, the initial meshing on the start image, for example I_2, is transformed into a new meshing on the other image, for example I_1. Then pathological situations may then occur at the level of the new meshing, such as :

- reversals of finished elements : finished elements reverse and cover others, thus destroying the property of partitioning of the range of the image any meshwork needs to verify,
- overflowing of the peripheral nodes of the moved meshwork after applying movement vectors beyond the range of the image I_1 : certain pixels of the image I_2 can be associated with pixels of the image I_1 situated outside the range of the image I_1. This is not strictly a problem, but it may be advantageous to force the peripheral nodes of the moved meshwork to remain inside the range of the image I_1.

One object of the invention concerns a method for estimating movement in which the meshwork is optimised during estimation so as to obtain at the end of the method a meshwork adapted to the semantic contents of the images. To this effect, the finished elements are refined during the movement estimate.

Another object of the invention is to improve the effectiveness of the Gauss Newton method so as to optimise the movement vectors of the nodes of the meshwork. To this effect, this optimisation is carried out on several resolution levels of the images.

Finally, another aim of the invention is to provide a method for estimating movement so as to avoid aforesaid pathological situations. To this effect, the invention provides adding during the movement vectors optimisation step constraints so as to avoid these situations.

Also, the invention concerns a method for estimating the movement between two numerical images I_1 and I_2 with luminance Y_1 and Y_2 and intended to generate for each point of coordinates x,y of the image I_2 a movement vector $\vec{d}(x,y)=(d_x,d_y)$ so

as to form an image $\hat{I}_2$ from the image I_1 with luminance $\hat{Y}_2(x,y)=Y_1(x-d_x,y-d_y)$ which is an approximation of the image I_2, characterised in that it comprises the following steps :

(a) defining an initial model of finished elements comprising a meshing whose nodes are points of the image I_2, a movement vector at each node of said meshing, and an interpolation formula for calculating the value of the movement vector of each point of the image I_2 from the values of the movement vectors of the nodes of the mesh to which it belongs,

(b) optimising the value of the movement vectors of the model according to a differential method,

(c) calculating a variation E between the image I_2 and the image $\hat{I}_2$ for each finished element or mesh,

(d) carrying out a finer meshing on a discrete fraction of the set of finished elements determined according to a criterion relating to the variations E and allocating a movement vector to each new meshing node,

(e) repeating the steps (b), (c) and (d) on the model of finished elements obtained at the end of the preceding step (d) until a stoppage criterion is satisfied.

According to an improved embodiment, for each numerical image I_1 and I_2 in addition a set of R images I_j^r is defined with a level of resolution r and luminance Y_i^r with r taking the values (0,...,R-1) and i the values 1 and 2, the images I_1^0 and I_2^0 corresponding to the numerical images I_1 and I_2, the steps (b) to (e) being conducted for each level of resolution r from the level r=R-1 to the level r=0.

Finally, according to a preferred embodiment, constraints are added to the movement of the finished elements at the time of optimising the movement vectors so as to avoid the reversal of the finished elements. According to another embodiment, it is also possible to introduce constraints so as to avoid the flowing over of the meshing obtained after applying the movement vectors beyond the sphere of the image I_1.

Other characteristics and advantages of the invention shall appear on a reading of

the following detailed description with reference to the accompanying drawings on which :

- figure 1 represents a diagram of a first embodiment of the movement estimation method of the invention ;
- figure 2 shows the step (d) of the method of the invention, and
- figure 3 shows a diagram of an improved embodiment of the movement estimation method of the invention.

Reference is first made to two numerical images I_1 and I_2 with respective luminance Y_1 and Y_2. The method of the invention consists of generating for each point P of coordinates (x, y) in the image I_2 a movement vector $\vec{d}(x,y)=(d_x,d_y)$. This vector is defined as being the vector able to construct from the image I_1 an image $\hat{I}_2$ with luminance $\hat{Y}_2(x,y)=Y_1(x-d_x,y-d_y)$ which is an approximation of I_2. The movements are thus defined from the image I_1 towards I_2.

The sought-after movement field is defined by a model of finished elements. In the remainder of the description, the finished elements are regarded to be triangles without there being any limitation of the extent of the present application to this form of finished elements. As a result, the model of finished elements comprises a triangular meshing, movement vectors defined in the meshing nodes, and an interpolation formula for calculating the movement vector of the points inside the triangles.

The interpolation formula used to calculate the movement field at any point of the range of the image I_2 is the following :

If the point P of coordinates (x,y) is considered in the image I_2 belonging to the triangle e with vertices P_i, P_j and P_k with respective coordinates (x_i,y_i), (x_j,y_j) and (x_k,y_k), its movement vector is equal to

$$\vec{d}(x,y) = \sum_{l=i,j,k} \Psi_l^e(x,y).\vec{d}(x_l,y_l)$$

where Ψ_l^e represents a basic function associated with the triangle e

In the case of an affine interpolation, the $\Psi_l^e(x,y)$ represent the barycentric coordinates of the point P in the triangle e with vertices P_i, P_j, P_k. These functions are defined by the following equation :

$$\begin{cases} \begin{cases} \Psi_l^e(x,y) = \alpha_l + \beta_l x + \gamma_l y & (x,y) \in e \\ \sum\limits_{l=i,j,k} \Psi_l^e(x,y) = 1 & \text{et} \quad \alpha_1, \beta_1, \gamma_1 \in \Re \end{cases} \\ \Psi_l^e(x,y) = 0 & (x,y) \notin e \end{cases}$$

namely $\Psi_i^e(x,y) = \dfrac{x_j y_k - x_k y_j + (y_j - y_k)x + (x_k - x_j)y}{x_j y_k - x_k y_j + x_k y_i - x_i y_k + x_i y_j - x_j y_i}$

The affine functions $\Psi_j^e(x,y)$ and $\Psi_k^e(x,y)$ deduced from the function $\Psi_i^e(x,y)$ by circularly permuting the indices i,j,k. It is also possible to use more evolved models of finished elements, the functions ψ then being able to be extended to polynomials with degree n=2, but the interpolation formula of the movement vectors then introduces first, second derivatives, etc. A miscellaneous choice of models of finished elements is shown in the work "Handbook of Numerical Analysis" by P.G. Ciarlet and J.L Lions, Volume 2, pages 59-99, published by North Holland.

According to the invention, as the movement is gradually estimated, the value of the movement vectors of the meshing nodes known as nodal vectors is optimised and the meshing is locally densified when this is necessary. Advantageously, this optimisation shall be carried out on several resolution levels starting with a low resolution level.

According to a first embodiment shown on figure 1, the method of the invention comprises five steps referenced (a) to (e).

according to this method is given by the following linear system :

$$D^{k+1} = D^k-[R^k + \alpha.I_{2N}]^{-1}.\nabla E^k \Leftrightarrow - H.\delta D^{k+1} = \nabla E^k \qquad (1)$$

with :

- D^{k+1} a column matrix of 2N elements including the components d_x and d_y of the nodal vectors on iteration k+1, N being the number of nodes of the meshing in the current step :
- D^k a column matrix of 2N elements including the components d_x and d_y of the nodal vectors on iteration k ;
- $H = [R^k + \alpha.I_{2N}]$
- I_{2N} the identity matrix with the dimension 2N ;
- $\nabla E^k = \begin{pmatrix} \nabla_x E^k \\ \nabla_y E^k \end{pmatrix}$ column matrix of 2N elements in which N elements $\nabla_{x,n}E^k$ and N elements $\nabla_{y,n}E^k$, n denoting a node of the meshing and taking in turn the values (1...N) ; with

$$\nabla_{x,n}E^k = 2.\sum_{e\in supp(n)}\sum_{(x,y)\in e} DFD_k(x,y).\frac{\partial I_1(x-d_x,y-d_y)}{\partial x}.\Psi_n^e(x,y)$$

$$\nabla_{y,n}E^k = 2.\sum_{e\in supp(n)}\sum_{(x,y)\in e} DFD_k(x,y).\frac{\partial I_1(x-d_x,y-d_y)}{\partial y}.\Psi_n^e(x,y)$$

where $DFD_k(x,y) = Y_2(x,y) - Y_1(x-d_x,y-d_y)$ on iteration k where sup p(n) represents the support of the basic function $\Psi_n^e(x,y)$ attached to the node n, that is all the triangles having the node n for a vertex ;

- $R^k = \begin{pmatrix} R^{k,xx} & R^{k,xy} \\ R^{k,yx} & R^{k,yy} \end{pmatrix}$ a square matrix with dimension 2N

where

$$R_{mn}^{k,xx} = 2.\sum_{e\in supp(mn)}\sum_{(x,y)\in e}\left(\frac{\partial I_1(x-d_x,y-d_y)}{\partial x}\right)^2.\Psi_m^e(x,y).\Psi_n^e(x,y)$$

$$R_{mn}^{k,yx} = 2.\sum_{e\in supp(mn)}\sum_{(x,y)\in e}\left(\frac{\partial I_1(x-d_x,y-d_y)}{\partial x}\right)\left(\frac{\partial I_1(x-d_x,y-d_y)}{\partial y}\right).\Psi_m^e(x,y).\Psi_n^e(x,y)$$

$$R_{mn}^{k,yx} = R_{mn}^{k,xy}$$

$$R_{mn}^{k,yy} = 2.\sum_{e\in supp(mn)}\sum_{(x,y)\in e}\left(\frac{\partial I_1(x-d_x,y-d_y)}{\partial y}\right)^2.\Psi_m^e(x,y).\Psi_n^e(x,y)$$

where m and n denote nodes of the meshing and take in turn the values $(1\ldots N)$ and where supp(nm)=supp(n) $\cap$ supp(m).

- $\alpha = \max_n\left(\left|\nabla_n E^k\right|.\left\|\Psi_n\right\|\right)$

where $\left\|\Psi_n\right\|$ is a functional norm of Ψ_n. The two most advantageous norms are :

$$\left\|\Psi_n\right\| = \sup_{(x,y)\in supp(n)}\left|\Psi_n(x,y)\right| = 1 \qquad \text{or}$$

$$\left\|\Psi_n\right\| = \sqrt{\frac{1}{\left|supp(n)\right|}\sum_{(x,y)\in supp(n)}\left[\Psi_n(x,y)\right]^2}$$

|supp(n)| denotes the cardinal number of the discrete region sup p(n).

At the end of this optimisation phase, there are available N nodal vectors each relating to one node of the meshing.

According to a variant embodiment of the adaptive gradient, it is possible to consider using a decomposition technique known as an "LDL^t profile" in technical language so as to resolve the linear system (1) and accelerate the treatment. This technique is described in the work entitled "Matrix numerical analysis applied to the art of the engineer" by Théodore Lascaux, Volume 1, pp 295-299, published by Masson, 1986.

According to an advantageous characteristic of the invention, the meshing is next locally refined via the division of triangles when the variation between the image $\hat{I}_2$ and the image I_2 on these triangles is too high. This is why according to the step (c) of the method a variation E is calculated between the image $\hat{I}_2$ and the image I_2 for each triangle e. The variation E is defined as follows :

$$E = \sum_{(x,y)\in e} DFD^2(x,y)$$

with $DFD(x,y) = Y_2(x,y) - Y_1(x-d_x, y-d_y)$

Of course, so as to calculate this variation for each triangle, it is necessary to firstly have calculated the value of the movement vectors of all the points of the image I_2 by means of interpolation from the nodal vectors obtained at the end of step (b).

Then in accordance with step (d), the meshing is refined on a discrete fraction of all the triangles of the model. This fraction is determined according to a criterion relating to the variations E previously calculated in step (c). So as to carry out this refining, it is possible for example to classify the triangles of the model by a decreasing order of their variations E and subdividing the X first triangles of this classification into smaller triangles. X is a predetermined fraction of the number of finished elements in the model, for example half.

So as to locally refine the meshing, it is also possible to compare all the variations E calculated in step (c) with a threshold variation which depends on the size of the finished element in question and of subdividing into smaller finished elements the finished elements whose variations E are greater than the threshold variation.

The subdivision of a triangle e into four smaller triangles is shown on figure 2. The triangle e is defined by the three vertices P_1, P_2 and P_3 having for respective movement vectors $\vec{d}_1$, $\vec{d}_2$, $\vec{d}_3$. So as to subdivide it into four, three new nodes P_4, P_5, P_6 are defined in the middle of the three sides P_1P_3, P_1P_2, P_2P_3 of the triangle. Allocated to each of these three new nodes is a movement vector equal to the

average of the movement vectors of the two tops of the side to which it belongs, respectively $(\vec{d}_1+\vec{d}_3)/2$, $(\vec{d}_1+\vec{d}_2)/2$, $(\vec{d}2+\vec{d}_3)/2$. The adjacent triangles to the triangle e whose side is P_1P_2, P_2P_3 or P_1P_3 are then subdivided into two or three.

Thus a model of finished elements is obtained whose meshing has been locally refined. According to step (e), steps (b), (c) and (d) are repeated at the end of the preceding step (d). This succession of steps is then repeated until a stoppage criterion is satisfied. This stoppage criterion is for example a predetermined number of finished elements to be reached at the end of step (d).

It is also possible to stop the method when the variations E of all these finished elements of the model obtained at the end of the preceding step (c) are lower than a threshold variation.

According to an improved embodiment shown on figure 3, the steps (b) to (e) are carried out by depending on several resolution levels of images I_1 and I_2. The aim of this variant is to improve and accelerate the convergence of the calculations of the movement vectors. In order to achieve this, first of all for each pair of numerical images I_1 and I_2, a set of R images I_i^r is defined with a level of resolution r and luminance Y_i^r, r taking in turn the values (R-1, R-2,...0) and i the values (1, 2) and then steps (b) to (e) are carried out for each level of resolution r from the level of resolution r=R-1 to the level r=0. It is to be noted that the images I_1^0 and I_2^0 correspond to the numerical images I_1 and I_2.

In practice, the images I_j^r are obtained by the filtering of the image I_i using a linear low pass filter only allowing $1/2^r$ of the spectral band of the image in question in the directions x and y, that is a pulse response filter h_n^r having a pass-band $BP_r=[1/2^{r+1}, 1/2^{r+1})$ in the space of standardised frequencies [-1/2, 1/2]. The image I_i^r is defined by the following equation :

$$Y_i^r(x,y)=\sum_{u=-M}^{M}\sum_{v=-M}^{M}Y_i(x-u,y-v)h_u^r h_v^r$$

The filter used is for example an approximation of an ideal filter and its pulse response is defined as follows :

$$h_n^r = \frac{s_n^r}{S} \quad \text{with} \quad S = \sum_{n=-M}^{M} s_n^r \qquad -M \leq n \leq M$$

$$\text{and } s_n^r = 2B.\operatorname{sinc}(2\pi B_r n) = 2B\frac{\sin 2\pi B_r n}{2\pi B_r n}$$

$$B_r = \frac{1}{2^{r+1}}$$

where B and M are natural integers
$M = +\infty$ in the ideal case.

As indicated previously, this optimisation on several resolution levels is able to improve and accelerate the convergence of the calculations of the movement vectors. It is to be noted that the number of resolution levels R selected may differ from the number of successive refinings carried out on the meshing.

According to a preferred embodiment, compactness constraints are added on each triangle of the model so as to prevent the triangles from reversing.

The compactness of a triangle with vertices P_i, P_j and P_k is defined by the following equation :

$$C(P_i,P_j,P_k) = \frac{4 \times \pi \times S(P_i,P_j,P_k)}{P^2(P_i,P_j,P_k)}$$

with $C(P_i,P_j,P_k) \in]0,1[$; and $S(P_i,P_j,P_k)$ et $P(P_i,P_j,P_k)$ representing respectively the surface and perimeter of the triangle (P_i, P_j, P_k)

If the compactness of a triangle is prevented from tending towards zero, it is also prevented from reversing. This is why, so as to avoid the reversals of triangles, each triangle must verify the following constraint :

$$C\left(P_i+\vec{d}_{P_i},P_j+\vec{d}_{P_j},P_k+\vec{d}_{P_k}\right)\geq K\times C\left(P_i,P_j,P_k\right)$$

$$\Leftrightarrow K\times C\left(P_i,P_j,P_k\right)-C\left(P_i+\vec{d}_{P_i},P_j+\vec{d}_{P_j},P_k+\vec{d}_{P_k}\right)\leq 0$$

$$\Leftrightarrow g_e\left(\vec{D}\right)\leq 0 \;\;;\;\; e=\text{triangle}\left(P_i,P_j,P_k\right)$$

where K is a parameter fixing the authorised compactness variation and $\vec{D}$ is the column vector of the movement vectors of the nodes of the model.

According to the invention, this constraint is associated with each triangle at the time the movement vectors are optimised. The step for optimising the movement vectors amounts to a system of the type :

$$\begin{cases} \min_{\vec{D}} E\left(\vec{D}\right) \\ g_e\left(\vec{D}\right)\leq 0 \qquad \forall e\in I \\ \vec{D}\subset\Re^{2N} \end{cases}$$

where:

- $E(\vec{D})$ represents the variation between the image I_2 and the said image $\hat{I}_2$;
- g_e is a constraint related to the triangle e ;
- I is the set of the triangles of the meshing.

So as to resolve the optimisation problems under constraints, the so-called increased Lagrangian technique is used. This technique is described in the work entitled "Theories and algorithms" by Michel Minoux, Volume 1, pp 257-260, published by Dunod 1983. This technique combines two optimisation techniques : Lagrangian optimisation and the optimisation of external penalties.

According to this technique, resolving the preceding system amounts to resolving the system without constraints according to :

$$\min_{\vec{D}}\left(E\left(\vec{D}\right)+\sum_{e\in I}G\left(g_e\left(\vec{D}\right),\lambda_e,r_e\right)\right)$$

Where r_e is a penality element,

λ_e is a Lagrange multiplier

G is an increased Lagrangian determined by the equation :

$$G\left(g_e(\vec{D}), \lambda_e, r_e\right) = \begin{cases} \lambda_e g_e(\vec{D}) + r_e g_e(\vec{D}) & \text{si } r_e > 0 \text{ et } g_e(\vec{D}) \geq 0 \\ \lambda_e g_e(\vec{D}) & \text{si } r_e = 0 \text{ et } g_e(\vec{D}) \geq 0 \\ 0 & \text{si } g_e(\vec{D}) \leq 0 \end{cases}$$

The constraints g_e have been previously linearised by the Taylor formula to the order 1 :

$$g_e(\vec{D}) \approx g_e(P_i, P_j, P_k) + \sum_{P_l = P_i, P_j, P_k} \vec{d}_{P_l} \frac{\partial g_e}{\partial \vec{d}_{(P_i, P_j, P_k)}}(P_l)$$

The optimisation method is then the following :

- k=0 is initialised
- λ = 0 and r=0 are placed, $\lambda \in \Re^m$ and $r \in \Re^m$, and m denotes the number of triangles of the model
- then the minimum $\delta D_{k+1}(\lambda, r)$ is determined so that on iteration k+1,

$$- H.\delta D^{k+1} = \nabla E^k - C^t\gamma$$

where $\gamma^t=(\lambda, r)$, C^t is a matrix of $\Re^{2N} \times \Re^{2m}$

$C^t\gamma$ forms a matrix of the linearised constraints having for coefficients the following values :

$$C_{ij} = \begin{cases} 0 & \text{si } g_e(\vec{D}) \leq 0 \\ \begin{cases} \partial_{\vec{d}_{P_l}} g_e(P_i, P_j, P_k) & \text{si } P_l = P_i, P_j \text{ ou } P_k \\ 0 & \text{sinon} \end{cases} & \text{sinon} \end{cases}$$

where e represents the triangle with the vertices P_i, P_j and P_k.

Then λ is updated by the Uzawa algorithm and r is increased. Then the preceding operation is repeated until all the constraints are verified before moving on to iteration k+2. It is to be noted that details of the Uzawa algorithm are given

in the work entitled "Theories and algorithms" by Michel Minoux, Volume 1, published by Dunod 1983.

According to a final embodiment, it is also possible to introduce constraints so as to avoid the flowing over of the meshing obtained after applying the movement vectors beyond the range of the image I_1. This embodiment consists of forcing the peripheral nodes of the meshing to remain on the edges of the image after applying movement vectors. In order to do this, the abscissae components δD^{k+1} for the peripheral nodes on the left and right edges of the image I_2 are cancelled on each iteration k. Similarly, the ordinate components δD^{k+1} for the upper and lower edges of the image I_2 are cancelled on each iteration k.

In the case of a coding application, associated with the meshing is a partially quaternary tree. On each subdivision of the meshing (step d), an additional level is added in the tree. Each level of the tree then represents a meshing level and each node of the tree represents a triangle of the corresponding meshing level. The binary train generated during the coding step is obtained via a reading of the tree level by level. In this binary train, the movement vectors associated with each node of the tree are advantageously coded differentially with respect to the movement vectors of their father node when the latter exists and are arranged level by level. The corresponding decoding step consists of regenerating this tree from the binary train received derived from the encoder.

CLAIMS

1. Method for estimating the movement between two numerical images I_1 and I_2 with luminance Y_1 and Y_2 for generating for each point of coordinates x,y of the image I_2 a movement vector $\vec{d}(x,y)=(d_x,d_y)$ so as to form an image $\hat{I}_2$ from the image I_1 with luminance $\hat{Y}_2(x,y)=Y_1(x-d_x,y-d_y)$ which is an approximation of the image I_2, characterised in that it comprises the following steps :

(a) defining an initial model of finished elements comprising a meshing whose nodes are points of the image I_2, a movement vector at each node of said meshing, and an interpolation formula for calculating the value of the movement vector of each point of the image I_2 from the values of the movement vectors of the nodes of the mesh to which it belongs,

(b) globally optimising the values of all the movement vectors of the model according to a differential method,

(c) calculating a variation E between the image $\hat{I}_2$ and the image I_2 for each finished element or mesh,

(d) carrying out a finer meshing on a discrete fraction of all the finished elements determined according to a criterion relating to the variations E and allocating a movement vector to each new meshing node,

(e) repeating the steps (b), (c) and (d) on the model of finished elements obtained at the end of the preceding step (d) until a stoppage criterion is satisfied.

2. Method according to claim 1, characterised in that, so as to carry out a finer meshing on a discrete fraction of all the finished elements in step (d), said set of finished elements is classified in the decreasing order of their variations E and the X first finished elements of this classification are subdivided into smaller finished elements, X representing a predetermined fraction of the number of finished elements of the set.

3. Method according to claim 1, characterised in that, so as to carry out a finer meshing on a discrete fraction of the set of finished elements in step (d), the set of variations E calculated in step (c) is compared with a threshold variation which

depends on the size of the finished element in question, and the finished elements whose variations E are greater than the threshold variation are subdivided into smaller finished elements.

4. Method according to one of claims 1 to 3, characterised in that said stoppage criterion is a predetermined number of finished elements constituting the model of finished elements to be reached at the end of step (d).

5. Method according to one of claims 1 to 3, characterised in that said stoppage criterion of step (e) is satisfied when the variations E of the set of finished elements of the model obtained at the end of the preceding step (d) are smaller than a functional threshold variation which depends on the size of the finished elements in question.

6. Method according to one of claims 1 to 5, characterised in that in addition for each numerical image I_1 and I_2, a set of R images I_i^r with a level of resolution r and luminance Y_i^r with r taking the values (0,....R-1) and i the values 1 and 2 is defined, the images I_1^0 and I_2^0 corresponding to the numerical images I_1 and I_2, and in that the steps (b) to (e) are carried out for each resolution level r from the level r=R-1 to the level r=0.

7. Method according to claim 6, characterised in that the sets of R images with resolution level r are obtained by filtering the images I_1 and I_2 along the two directions x and y using a low-pass filter with a pulse response h_n^r , each image I_i^r being defined by the following equation :

$$Y_i^r(x,y) = \sum_{u=-M}^{M} \sum_{v=-M}^{M} Y_i(x-u, y-v) h_u^r h_v^r$$

with M a natural integer.

8. Method according to claim 7, characterised in that the pulse response h_n^r is defined as follows :

$$h_n^r = \frac{s_n^r}{S} \quad \text{avec} \quad S = \sum_{n=-M}^{M} s_n^r$$

$$s_n^r = 2B.\operatorname{sinc}(2\pi B_r n) = 2B\frac{\sin 2\pi B_r n}{2\pi B_r n}$$

$$B_r = \frac{1}{2^{r+1}}$$

B being a natural integer.

9. Method according to one of the preceding claims, characterised in that the initial movement vectors are nil vectors.

10. Method according to one of the preceding claims, characterised in that the variation E between the image $\hat{I}_2$ and the image I_2 for each finished element e is defined by the following equation :

$$E = \sum_{(x,y)\in e} DFD^2(x,y)$$

where $DFD(x,y) = Y_2(x,y) - Y_1(x-d_x, y-d_y)$

11. Method according to one of the preceding claims, characterised in that the interpolation formula for calculating the value of the movement vector of a point P of coordinates (x,y) in the image I_2 belonging to the finished element e with vertices P_i, P_j and P_k with respective coordinates (x_i,y_i), (x_j,y_j) et (x_k,y_k) is the following :

$$\vec{d}(x,y) = \sum_{l=i,j,k} \Psi_l^e(x,y).\vec{d}(x_l,y_l)$$

where ψ_l is a function of the form

$$\begin{cases} \begin{cases} \Psi_l(x,y) = \alpha_l + \beta_l x + \gamma_l y & (x,y) \in e \\ \sum_{l=i,j,k} \Psi_l(x,y) = 1 & \end{cases} \\ \Psi_l(x,y) = 0 & (x,y) \notin e \end{cases}$$

12. Method according to one of claims 1 to 11, characterised in that the differential method for optimising the movement vectors is the Gauss-Newton method.

13. Method according to one of claims 1 to 11, characterised in that the differential method for optimising the movement vectors is the Marquardt extension of the Gauss-Newton method.

14. Method according to one of the preceding claims, characterised in that a compactness constraint is imposed on each finished element at the time of optimising the movement vectors of the model of finished elements, said constraint consisting of preventing the compactness of each finished element from tending to zero.

15. Method according to claim 14, characterised in that the compactness constraint on a finished element e with vertices P_i, P_j, P_k and compactness C (P_i,P_j,P_k) is defined by the following equation :

$$C\left(P_i + \vec{d}_{P_i}, P_j + \vec{d}_{P_j}, P_k + \vec{d}_{P_k}\right) \geq K \times C\left(P_i, P_j, P_k\right)$$

where $\vec{d}_{P_i}$, $\vec{d}_{P_j}$, et $\vec{d}_{P_k}$ represent the movement vectors of the vertices P_i, P_j, P_k during the optimisation step, and K is a compactness parameter.

16. Method according to claim 14 or 15, characterised in that the optimisation of the movement vectors under constraints on the finished elements is resolved by the increased Lagrangian technique.

17. Method according to claim 16, characterised in that the constraints are used in a linearised form in the increased Lagrangian technique.

18. Method according to one of claims 12, 13 or 17, characterised in that the methods for optimising the movement vectors use an LDL^t profile technique.

19. Application of the method for estimating movement between two numerical images according to one of claims 1 to 18 for coding images, characterised in that the fractional subdivision of the meshing carried out in step d) of the movement estimation method is associated with a partially quaternary tree in which each level represents a meshing level and each node represents a triangle of the given level, and in that what is generated is a binary train describing said tree.

20. Application of the method for estimating movement between two numerical images according to claim 19, characterised in that the movement vectors associated with each node of said tree are encoded differentially with respect to the movement vectors of their father node when the latter exists and are ordered in said binary train along a width passage of said tree.

21. Application of the method for estimating movement between two numerical images according to one of claims 1 to 18 for decoding images, characterised in that the fractional subdivision of the meshing carried out in step d) of the movement estimation method is associated with a partially quaternary tree in which each level represents a meshing level and each node represents a triangle of the given level, and in that said tree is generated from a binary train of encoded data describing said tree.

22. Application of the method for estimating movement between two numerical images according to claim 21, characterised in that the encoded data relating to a given level of the tree are collectively regrouped in the binary train so as to generate the tree level by level as the train is read.

23. Application of the method according to one of the preceding claims to at least one of the ranges belonging to the group of the following ranges :

- compression of sequences of images, and
- compression of data in spaces larger than 2.

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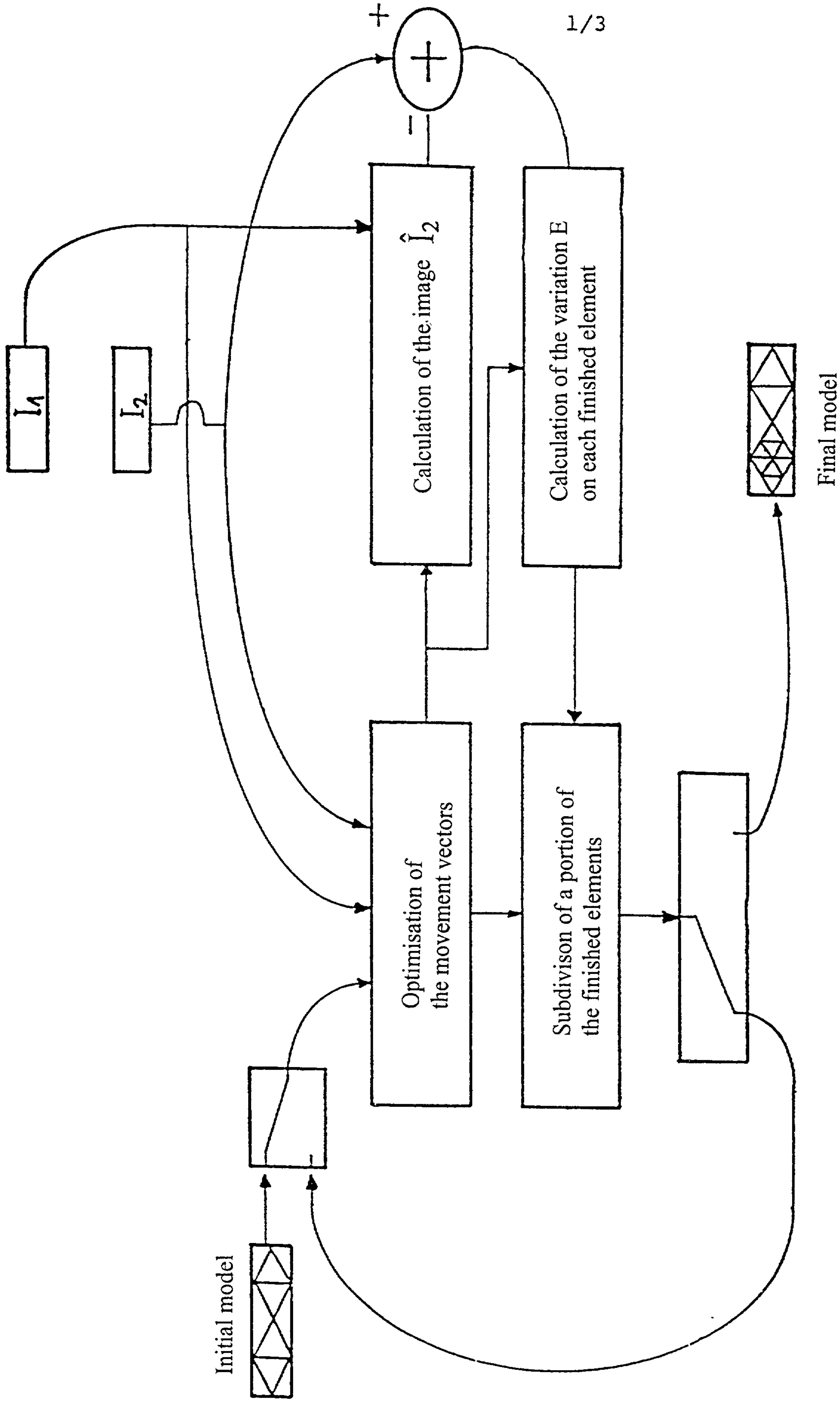
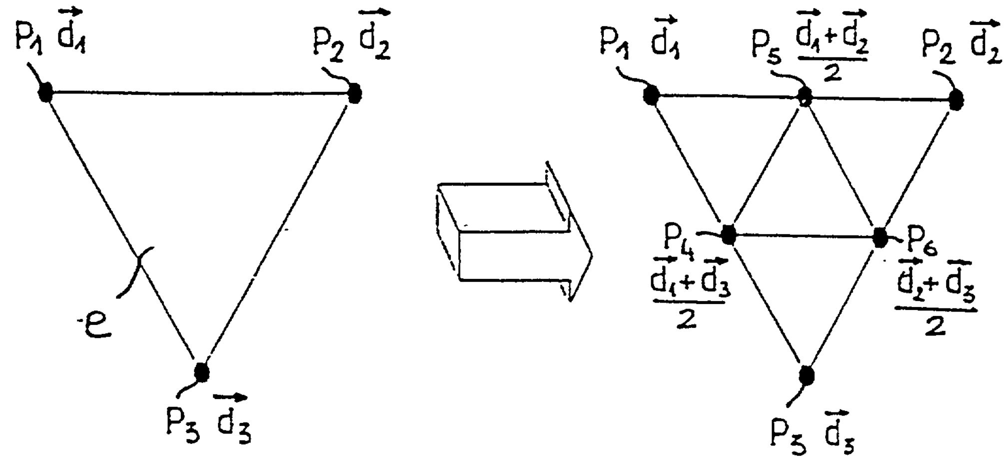
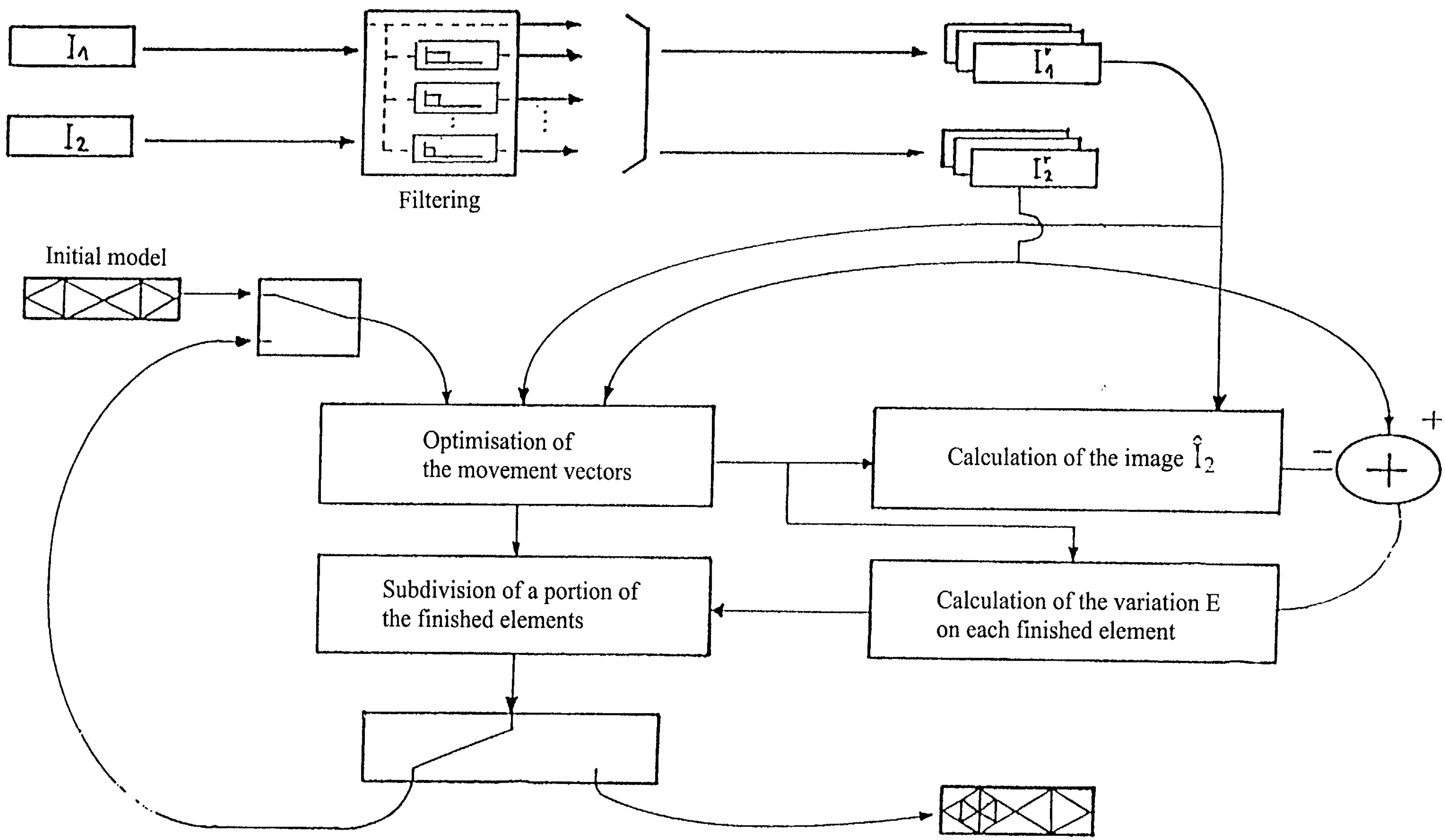


FIG.1



$P_1\ \vec{d}_1$
$P_2\ \vec{d}_2$
$P_3\ \vec{d}_3$
e
$P_1\ \vec{d}_1$
$P_5\ \frac{\vec{d}_1+\vec{d}_2}{2}$
$P_2\ \vec{d}_2$
$P_4\ \frac{\vec{d}_1+\vec{d}_3}{2}$
$P_6\ \frac{\vec{d}_2+\vec{d}_3}{2}$
$P_3\ \vec{d}_3$

FIG.2



I_1
I_2
Filtering
I_1^r
I_2^r
Initial model
Optimisation of the movement vectors
Calculation of the image $\hat{I}_2$
+
−
Subdivision of a portion of the finished elements
Calculation of the variation E on each finished element
Final model

FIG.3

03051

DECLARATION FOR UTILITY OR DESIGN PATENT APPLICATION (37 CFR 1.63)

☐ Declaration Submitted with Initial Filing
OR
☒ Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16(e)) required)

Attorney Docket Number: 136.157
First Named Inventor: Nathalie LAURENT-CHATENET
COMPLETE IF KNOWN
Application Number: 09/786 173
Filing Date:
Group Art Unit:
Examiner Name:

As a below named inventor, I hereby declare that:

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

the specification of which
☐ is attached hereto
OR
☒ was filed on ____________ as United States Application Number or PCT International Application Number 09/786 173 and was amended on ____________ (if applicable).

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the patentability as defined in 37 CFR 1.56.

I hereby claim foreign priority benefits under 35 U.S.C. 119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate, or of any PCT international application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)

(Number)	(Country)	(Month/Day/Year Filed)	Priority Not Claimed	Certified Copy Attached?
98 11227	FRANCE	September 04, 1998	☐	☐ Yes ☐ No
PCT/FR99/02076	FRANCE	September 1, 1999	☐	☐ Yes ☐ No
			☐	☐ Yes ☐ No

☐ Additional foreign application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto:

I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

(Application Number)	(Month/Day/Year Filed)

☐ Additional provisional application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.

DECLARATION – Utility or Design Patent Application

Inventor(s): Nathalie LAURENT-CHATENET
Title: Method for estimating movement between two images.

I hereby claim the benefit under 35 U.S.C. 120 of any United States application(s), or 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT international application in the manner provided by the first paragraph of 35 U.S.C. 112, I acknowledge the duty to disclose information which is material to the patentability as defined in 37 CFR 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

U.S. Parent Application or PCT Parent Application(s)

(Number)	(Month/Day/Year Filed)	(Patent Number (if applicable))
PCT/FR99/02076	September 01, 1999	

☐ Additional U.S. or PCT international application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.

As a named inventor, I hereby appoint the following registered practitioner(s) to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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(3) over

DECLARATION – Utility or Design Patent Application

Inventor(s): Nathalie LAURENT-CHATENET
Title: Method for estimating movement between two images.

3-00

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